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Research Article

Integrated Wastewater Treatment and Resource Recovery for A Circular Economy Model in Decentralized Communities: A Case Study of Military Battalion in Vietnam

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Abstract

Decentralized communities, including remote military battalions, often lack centralized wastewater treatment infrastructure, resulting in pollution from livestock wastewater. This study developed a low-cost circular economy system for a military battalion in Thai Nguyen Province, combining mechanical solid–liquid separation, a combined anaerobic–aerobic biological reactor, and a subsurface-flow constructed wetland planted with elephant grass (Pennisetum purpureum). The system was operated at 12–15 m^3 day^{-1} to treat piggery wastewater while nutrients were recovered for onsite agricultural reuse. The system was monitored over a 10-month period, comprising a 2-month startup phase and 8 months of stable operation. The system achieved removal efficiencies of 84.5% for BOD_5, 84.7% for COD, 53.3% for TSS, and 91.7% for coliform, consistently meeting Vietnamese discharge standards (QCVN 62-MT:2016/BTNMT). The effluent retained nutrient levels (approximately 116 mg TN L^{-1} and 12.5 mg TP L^{-1}), enabling its direct use as a liquid fertilizer. When combined with compost produced from separated solids, the recycled nutrient system supported *Brassica juncea* (mustard greens) growth under the four nutrient management treatments. Compared with conventional chemical fertilization (36.46 t ha^{-1}), the treatment using recycled effluent plus high-dose compost (15 t·ha-1) resulted in a 23.6% higher marketable yield (45.05 t ha^{-1}). Nitrate, heavy metal, and *E. coli* concentrations in harvested vegetables remained within Vietnamese food safety standards. The circular system generated a net economic benefit of approximately 31.67 million VND ha^{-1} $crop^{-1}$ $cycle^{-1}$ through the elimination of chemical fertilizers and increased crop revenue when it was operating at low energy intensity (0.25 kWh m^{-3}). This hybrid nature-based system demonstrated promising technical performance and agronomic benefits under the pilot conditions studied. However, longer-term monitoring and comprehensive nutrient balance analyses are recommended to fully validate system sustainability and the potential for fertilizer substitution. The approach offers a practical model for decentralized military and rural communities in tropical regions.

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Introduction

Rapid urbanization and expanding agricultural activities in developing countries have intensified the pressure on water resources, particularly in decentralized and remote communities where centralized wastewater infrastructure is absent or unfeasible. Military battalions, remote rural settlements, island communities, and mountainous regions exemplify such settings. In Vietnam, numerous military units operate small- to medium-scale livestock farms to support food self-sufficiency, generating substantial volumes of high-strength piggery wastewater that is frequently discharged with minimal or no treatment. This practice leads to severe localized pollution, including oxygen depletion, eutrophication, odor nuisance, and pathogen spread, which threaten both environmental and human health (Nguyen et al., 2020; Tang et al., 2026).

Conventional centralized or mechanical treatment technologies, such as activated sludge systems or upflow anaerobic sludge blanket (UASB) systems, are often unsuitable for these decentralized contexts. They require high capital investment, intensive energy consumption (typically 0.3–1.5 kWh m^{-3} for activated sludge and similar for UASB with posttreatment), skilled operators, and continuous maintenance—factors that are prohibitive in remote military or rural areas with limited infrastructure and budget constraints (Brault et al., 2022; Rattier et al., 2022). Moreover, these systems are designed primarily for pollutant removal rather than resource recovery, resulting in the permanent loss of valuable nutrients (nitrogen and phosphorus) and organic matter that could otherwise support local agriculture. In response to these limitations, there has been a global shift from linear “waste treatment” approaches toward “resource recovery” within the circular economy (CE) framework. The CE concept aims to transform wastewater from a liability into a valuable resource by recovering water, nutrients, energy, and organic matter for beneficial reuse (Qadir et al., 2020; Soo et al., 2024; Wada et al., 2026). Nature-based solutions (NBSs), particularly constructed wetlands (CWs) combined with biological pretreatment, have emerged as promising, low-energy, low-maintenance technologies for decentralized settings. Recent studies confirm that hybrid CW systems can achieve high removal of organic matter and pathogens while intentionally retaining nutrients for agricultural irrigation, aligning perfectly with circular principles (Barresi et al., 2025; Corrêa et al., 2025; Gogoi et al., 2024; Rizzo et al., 2023).

This study evaluates the performance of a tailored, integrated decentralized system deployed at a Vietnamese military battalion (Battalion 3, Regiment 246, Military Region 1). The system combines mechanical solid–liquid separation, a combined anaerobic–aerobic biological reactor with proprietary filter media, and a subsurface-flow constructed wetland planted with elephant grass (*Pennisetum purpureum*). Designed to treat 12–15 m^3 day^{-1} of piggery wastewater, the system simultaneously produces polished effluent suitable for irrigation and compost from separated solids. The primary objective is to assess the technical efficiency of pollutant removal, the agronomic value of the recovered nutrients for *Brassica juncea* (mustard greens) production, and the overall economic and environmental benefits of this circular model under real military operating conditions. By demonstrating that treated livestock wastewater can fully replace chemical fertilizers while increasing crop yields, this research provides a practical model for circular sanitation in decentralized military units and similar remote communities across tropical developing regions. The findings contribute directly to several United Nations Sustainable Development Goals, particularly SDG 6 (Clean water and sanitation), SDG 12 (Responsible consumption and production), and SDG 13 (Climate action).

Materials and methods

1) Study site and system description

The field study was conducted at a Military Battalion (d3), which is located in a rural area of northern Vietnam. A battalion is a basic combat unit of the Vietnam People's Army, with fewer than 1,000 people. With a large number of soldiers and high daily food consumption and many battalions stationed far from major markets, food sourcing is difficult. To ensure a stable food supply for the troops, many units have recently prioritized increasing agricultural production on a basic, medium-scale, and sustainable basis. These production activities include mainly pig farming (approximately 200–250 pigs per battalion), poultry farming, and vegetable cultivation. Daily piggery wastewater generation was estimated at 12–15 m^3 day^{-1} (average of 60 L $head^{-1}$ day^{-1}, on the basis of direct measurements and literature values for tropical conditions). The site represents a typical decentralized community in remote or semiremote military settings, where centralized sewerage infrastructure is absent, and wastewater is typically discharged with minimal or no treatment, resulting in localized soil and water pollution. A decentralized, integrated wastewater treatment and resource recovery system was designed, constructed, and operated to treat piggery wastewater and enable safe agricultural reuse. The system (design flow rate of 15 m^3 day^{-1}) comprises four main process units operated in series (Figure 1).

a) *Solid–liquid separation unit*: Wastewater from the pig pens is collected in a 23 m^3 reinforced-concrete equalization tank (4.0 m × 2.9 m × 3.0 m). A screw-press separator (1.5 kW, capacity of 1–3 m^3 h^{-1}) separates solids (used as the compost feedstock) from the liquid.

b) *Combined anaerobic–aerobic biological reactor*: A 52.5 m^3 five-compartment tank (5.0 m × 3.0 m × 3.5 m) filled with proprietary filter media. The reactor operates in alternating anoxic and oxic zones to achieve simultaneous organic carbon oxidation and partial nitrogen removal.

Suspended plastic biofilm carriers designed for moving bed biofilm reactor (MBBR) systems were used in the combined anaerobic–aerobic biological reactor. The carriers were fabricated from high-density polyethylene (HDPE) or polyethylene (PE) and featured a hollow, porous structure with a high specific surface area of 800–900 m^2 m^{-3}.

c) *Subsurface-flow constructed wetland (SFCW) polishing unit*: A horizontal subsurface-flow wetland (total surface area ≈ 42 m^2; depth 0.8 m) was planted with elephant grass (*Pennisetum purpureum*) at 0.2 m × 0.2 m spacing. The bed media consists of graded gravel, sand, and soil layers over an HDPE liner.

d) *Effluent storage and reuse tank*: An 18.1 m^3 concrete tank (5.0 m × 2.5 m × 1.45 m) for temporary storage of polished effluent before drip or furrow irrigation of the vegetable plots.

All the units were constructed with locally available materials and operated under gravity flow where possible, with minimal pumping (total power consumption of 3.75 kWh day^{-1}). The system was commissioned in October 2023 and monitored for three months under steady-state conditions. A parallel area for vegetable cultivation (≈ 500 m^2) within the battalion production garden was used for the agricultural reuse trials.

2) Experimental design

The experiment was divided into two sequential phases.

Phase 1 – Treatment performance monitoring (September 2023 – June 2024): The performance of the decentralized piggery wastewater treatment system at the military battalion was monitored for more than 10 months, comprising a 2-month startup (maturation) phase followed by 8 months of stable operation. This extended monitoring campaign was designed to capture representative climatic conditions characteristic of northern Vietnam, including both the hot and cold seasons, thereby enabling a comprehensive evaluation of system stability and long-term treatment performance under realistic field conditions. During the startup phase, grab samples of wastewater (influent, intermediate samples from the combined anaerobic–aerobic biological reactor, and final effluent) were collected twice per month. Once steady-state operation was achieved, the sampling frequency was reduced to once every two months. All samples were taken in triplicate between 08:00 and 10:00 to represent peak loading conditions. Grab samples (n = 3 per event) were taken between 08:00 and 10:00 to represent peak loading conditions.

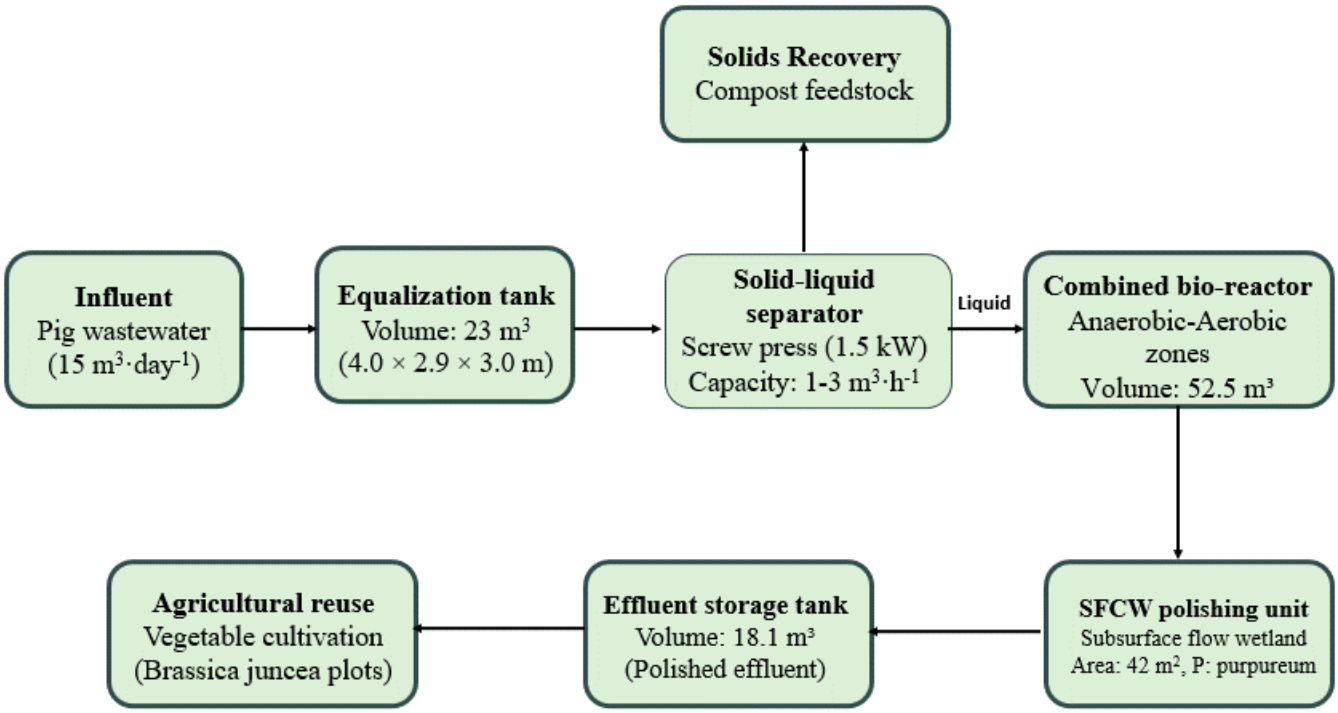


Figure 1 Schematic block diagram of the integrated decentralized wastewater treatment and resource recovery system.

Phase 2 – Agricultural reuse trial (June 2024 – September 2024): A field experiment was established to assess the feasibility of using polished effluent as irrigation water and as a liquid fertilizer for *Brassica juncea* L. (mustard greens), a fast-growing leafy vegetable widely cultivated in northern Vietnam. The trial employed a randomized complete block design with four treatments and three replicates (plot size 2 m × 3 m,

25 plants m^{-2}). All the plots received the same volume of irrigation water (≈ 5 mm day^{-1}) but differed in nutrient supplementation:

- *CT1 (Control – conventional practice)*: Well water + standard chemical NPK fertilizer applied according to local extension recommendations (120 kg N, 60 kg P_2O_5, 60 kg K_2O ha^{-1}).
- *CT2*: Recycled effluent + low-dose compost (5 t ha^{-1}).
- *CT3*: Recycled effluent + medium-dose compost (10 t ha^{-1}).
- *CT4 (Optimal recycled treatment)*: Recycled effluent + high-dose compost (15 t ha^{-1}, equivalent to the nutrient load recovered from the piggery solids).

This mapping allows direct comparisons between conventional chemical-based production (CT1) and a fully circular system that relies primarily on recovered nutrients (CT4). The seeds were sown in October 2023; transplanting occurred at the 4-leaf stage. The crop duration ranged from 47–51 days.

3) Sampling and analytical methods

Wastewater samples were collected in precleaned polyethylene bottles, preserved on ice, and transported to the laboratory within 4 h. Physicochemical parameters were analyzed according to standard methods (APHA, 2017) or equivalent Vietnamese national standards (TCVN):

- pH: electrometric method (TCVN 5979:2008)
- BOD_5: 5-day incubation at 20 °C (TCVN 6001:2008)
- COD: dichromate closed reflux (TCVN 6491:1999)
- TSS: gravimetric filtration (TCVN 6625:2000)
- Total nitrogen (TN): Kjeldahl digestion and distillation method (TCVN 6498:2011)
- Total phosphorus (TP): The ascorbic acid method after persulfate digestion (TCVN 6202:2008)
- Coliforms: multiple-tube fermentation technique (TCVN 8775:2011)
- *Escherichia coli (E. coli)* in harvested vegetables: Colony-count method on chromogenic media at 44 °C (TCVN 7924-3:2008; equivalent to ISO 16649-2:2001)
- Nitrate and nitrite in harvested *Brassica juncea:* molecular absorption spectrophotometric method (TCVN 7767:2007; equivalent to ISO 6635:1984)

Compost maturity was verified in accordance with QCVN 01-189:2019/BNNPTNT (temperature, C/N ratio, germination index). The plant growth parameters (plant height, number of leaves, and canopy diameter) were measured weekly using a ruler and a digital caliper. Fresh and dry biomass were determined at harvest. All analyses were performed in triplicate; quality control included blanks, duplicates, and certified reference materials.

4) Data Analysis

The removal efficiency was calculated as shown in Eq. 1.

$$\text{Removal (\%)} = [(C_{influent} - C_{effluent})/C_{influent}] \times 100 \quad \text{(Eq.1)}$$

where C is the concentration of the respective parameter.

For the agricultural trial, the data were analyzed using one-way analysis of variance (ANOVA), followed by Tukey's HSD post hoc test at $\alpha = 0.05$, in SPSS version 26.0. The results are presented as the mean ± standard deviation. Pearson correlation analysis was performed to explore the relationships between residual nutrient concentrations in the effluent and crop performance parameters. All figures were prepared using OriginPro 2026.

Results and discussion

1) Performance of the decentralized treatment system

Raw piggery wastewater generated at Battalion 3 exhibited high-strength organic and nutrient loads typical of intensive livestock production systems in tropical regions, particularly where wastewater is limited by dilution and no preliminary solid–liquid separation. Characterization at the collection pit (CNV1-HG) and the open discharge channel revealed considerable spatial and temporal variability in wastewater quality. This variability was primarily associated with fluctuations in pen-cleaning practices, direct contributions of urine and fecal matter, and the limited settling capacity of the wastewater conveyance system.

Only the pH remained within the regulatory limits, whereas all the other measured parameters exceeded the permissible values. Organic pollution levels were particularly high, with COD and BOD_5 concentrations far above the Vietnamese livestock wastewater discharge standards (Table 1). These concentrations are consistent with those reported for undiluted or minimally diluted swine wastewater across tropical Asia and Vietnam, where substantial variability is often associated with intensive smallholder and military-scale livestock operations, limited wastewater management infrastructure, and inadequate pretreatment practices (Nguyen et al., 2020; 2022; Nguyen and Soda, 2025). Such extreme organic loading poses serious environmental risks, including oxygen depletion, eutrophication, odor generation, and groundwater contamination if discharged without adequate treatment. These challenges have been widely documented in both military and smallholder pig farming systems in Vietnam (Nguyen and Soda, 2025).

The nutrient profile (total nitrogen (TN) concentration of 134.4–205.6±19.8 mg L^{-1} and total phosphorus (TP) concentration of up to 23.1±3.2 mg L^{-1}) further highlights both the environmental hazard and the circular economy opportunity (Table 1). These concentrations exceed typical domestic wastewater concentrations by 5–10-fold but fall within the optimal range for the fertigation of leafy vegetables after proper polishing (QCVN 01-195:2022/BNNPTNT). Coliform levels indicate substantial fecal contamination, necessitating effective pathogen barriers in the polishing stage. This high-strength, variable influent directly dictated the hybrid system design: upstream mechanical solid–liquid separation to divert organics for composting, followed by a combined anaerobic–aerobic biological reactor for primary organic breakdown and a subsurface-flow constructed wetland (SFCW) planted with elephant grass (*Pennisetum purpureum*) for final polishing and controlled nutrient retention. The configuration deliberately balances pollutant removal with resource preservation. The decentralized piggery wastewater treatment system at Battalion 3 was commissioned in September 2023. During the initial startup phase, the pollutant removal efficiency varied, and the effluent quality did not consistently comply with Vietnamese discharge standards (QCVN 62-MT:2016/BTNMT, Column B). This period reflected the time required for microbial community acclimation and the development of stable biofilms within the combined anaerobic–aerobic biological reactor and the subsurface-flow constructed wetland planted with elephant grass. The water quality monitoring results during the startup phase are presented in Table 2.

The monitoring results during the startup phase (Table 2) demonstrated a clear and progressive improvement in treatment performance over the 8-week period. The effluent concentrations of COD, BOD_5, total nitrogen, and total phosphorus decreased steadily from week 2 to week 8, corresponding to substantial increases in removal efficiency.

COD removal increased from 36.2% to 76.9%, whereas BOD_5 removal increased from 46.4% to 77.3%. The total nitrogen and total phosphorus removal efficiencies also improved markedly, reaching 43.8% and 40.3%, respectively, by week 8. These trends indicate successful microbial acclimation and the gradual development of stable biofilms within the biological reactor and the subsurface-flow constructed wetland.

Table 1 Raw piggery wastewater characteristics at Battalion 3

Parameter	Unit	Collection Pit (CNV1-HG)	QCVN 62-MT:2016/BTNMT (Column B)	Maximum Exceedance Factor (fold)
pH	–	7.7±0.2	5.5–9	Compliant
BOD_5	mg L^{-1}	615.4±48.5	100	26.5
COD	mg L^{-1}	1,800±135	300	14.9
TSS	mg L^{-1}	215.0±32.0	150	1.4
TN	mg L^{-1}	205.6±19.8	150	1.4
TP	mg L^{-1}	23.1±3.2	–	–
Coliform	CFU 100 mL^{-1}	12,000±2,800	5,000	1.9

Remark: Values for the collection pit are presented as the mean ± standard deviation (SD) for three sampling events (n = 3); "—" = no regulations.

Table 2 Water quality during the startup phase of the decentralized piggery wastewater treatment system

Parameter	Influent				Effluent				Removal efficiency (Week 8)
	Week 2	Week 4	Week 6	Week 8	Week 2	Week 4	Week 6	Week 8	
COD (mg L^{-1})	1818.55 ± 36.21	1682.62 ± 45.12	2025.28 ± 56.21	1705.37 ± 33.65	1160.53 ± 40.15	772.11 ± 33.25	582.28 ± 44.21	393.71 ± 21.63	76.91%
BOD_5 (mg L^{-1})	926.53 ± 20.62	1106.85 ± 40.85	1205.62 ± 27.36	868.36 ± 20.45	496.26 ± 26.45	526.68 ± 27.23	368.64 ± 20.16	197.54 ± 23.35	77.25%
TN (mg L^{-1})	206.85 ± 15.37	220.63 ± 9.35	268.32 ± 12.69	205.65 ± 11.35	174.55 ± 23.12	172.97 ± 13.56	160.44 ± 7.56	115.60 ± 10.49	43.79%
TP (mg L^{-1})	25.64 ± 1.26	35.87 ± 1.31	38.54 ± 5.36	26.54 ± 4.66	22.40 ± 15.21	28.54 ± 2.15	25.36 ± 1.58	15.85 ± 2.65	40.28%
TSS (mg L^{-1})	203.54 ± 20.21	268.97 ± 15.64	215.63 ± 11.45	198.66 ± 12.37	169.58 ± 8.35	172.74 ± 13.22	126.65 ± 22.10	100.65 ± 24.77	49.33%
Coliform (CFU 100 mL^{-1})	11,300 ± 2,500	10,400 ± 2,300	9,100 ± 2,700	5,800 ± 1,500	6,000 ± 100	5,500 ± 120	1000 ± 110	n.d (LOD=1)	100%

Remark: Values are presented as the mean ± standard deviation (SD) based on triplicate analyses (n = 3), "n.d" = "Not detected". "LOD" = "Limit of detection"

Influent wastewater characteristics fluctuated considerably across the sampling events, reflecting the operational practices at Battalion 3, where the pig pens were cleaned by daily flushing. Despite these variations in hydraulic and organic loading, the system maintained a consistent upward trajectory in removal performance, demonstrating notable resilience to shock loads. Coliform concentrations in the effluent also decreased substantially during this period. Organic matter removal (COD and BOD_5) performed well during the startup phase, with efficiencies exceeding 75% by week 8. In contrast, nutrient removal remained moderate, with total nitrogen and total phosphorus removal efficiencies reaching only 43.8% and 40.3%, respectively. This pattern is typical of conventional biological treatment systems, in which nitrogen and phosphorus are assimilated primarily into microbial biomass rather than being completely removed from the water column. At the end of the 8-week start-up period, the elephant grass in the constructed wetland had reached an average height of 90–100 cm and was still actively growing. Consequently, the system achieved stable and efficient organic matter removal but had not yet achieved optimal nutrient reduction. Therefore, performance evaluation was continued during the subsequent 8 months of stable operation to fully assess long-term treatment efficiency under varying seasonal and loading conditions. Therefore, the hybrid wastewater treatment system at Battalion 3, which integrates a combined anaerobic–aerobic biological reactor with a subsurface-flow constructed wetland planted with elephant grass, demonstrated effective and reliable performance in treating high-strength piggery wastewater. Throughout the stable operation phase, the effluent concentrations of organic matter and nutrients consistently complied with Vietnamese discharge standards (QCVN 62-MT:2016/BTNMT, Column B).

A significant increase in influent loading was observed in month 6 (February 2024). During this period, the concentrations of COD, BOD_5, and total nitrogen increased by approximately 1.5 to 3 times compared with those in month 4, reaching peak values of 1935.26± 38.65 mg L^{-1}, 1235.36± 46.34 mg L^{-1}, and 272.13 ± 20.12 mg L^{-1}, respectively. This temporary shock load was attributed to the annual military personnel rotation cycle typical of Vietnamese army units. Following the discharge of soldiers at the end of December, recruits are typically received in February and March, resulting in a sudden increase in the number of troops to full strength. Consequently, pig production was scaled up to meet food requirements, leading to elevated wastewater generation. This seasonal fluctuation in personnel strength creates a recurring “shock loading” pattern for wastewater treatment systems in military barracks. From month 8 onward, the influent concentrations decreased slightly and stabilized at moderately high levels (COD ≈ 1500 mg L^{-1}; BOD_5 ≈ 700–800 mg L^{-1}).

The system exhibited distinct removal patterns between organic matter and nutrients/solids. Organic matter removal (COD and BOD_5) remained high and stable throughout the operation phase. Notably, during the high-load period in month 6, the COD removal efficiency decreased only marginally from 91.7% to 89.6%, despite the cold winter–spring conditions and elevated organic loading. In subsequent months, the COD and BOD_5 removal efficiencies recovered and exceeded 95% during the warmer summer period. TSS removal was also stable and gradually improved over time. These results indicate that the microbial community responsible for organic degradation maintained robust activity under varying environmental and loading conditions. In contrast, total nitrogen removal showed clear seasonal variation, with the lowest efficiency (69.8%) recorded in month 6, which was during the colder months, when elephant grass plant growth and nitrification activity were reduced. TN removal subsequently recovered to approximately 70–71% in the summer months. Total phosphorus removal, however, tended to gradually increase over the monitoring period (from 71.1% to 76.1%), suggesting that phosphorus removal was driven primarily by cumulative adsorption onto the wetland media rather than by seasonal biological activity. Furthermore, the system effectively controlled toxicity and pathogenesis risks. After 8 months of operation, the concentrations of heavy metals (As, Cd, Cr, Hg, and Pb) in the effluent remained below the limit of detection, and the *E. coli* counts were either undetectable or well below the regulatory threshold. These results confirm that the treated effluent fully complied with QCVN 62-MT:2016/BTNMT (Column B) and met the safety requirements for agricultural reuse as irrigation water for vegetable crops and other vegetation.

As shown in Figure 2, the pollutant removal efficiency improved significantly over the system’s operating time. After 2 months of operation, the elephant grass root system in the filter bed developed strongly, with plants more than 150 cm tall, effectively removing most of the BOD, TSS and remaining bacteria in the wastewater. Organic matter removal increased rapidly: BOD_5 increased from 71.0% after the first month to 82.8% at 1.5 months and stabilized at 84.5% by the second month. Similarly, COD removal improved from 81.4% to 84.1% and then to 84.7%. These high and stable organic removal efficiencies (>84% for both BOD_5 and COD after maturation) indicate the strong biodegradation capacity of the hybrid system under tropical conditions.

Table 3 Water quality during the stable operation phase of the decentralized piggery wastewater treatment system

Parameter	Influent				Effluent				Removal efficiency (Week 8)	QCVN 62-MT:2016/BTNMT (Column B)
	Week 2	Week 4	Week 6	Week 8	Week 2	Week 4	Week 6	Week 8		
COD (mg L^{-1})	1026.35 ± 38.40	1935.26 ± 38.65	1529.65 ± 59.66	1536.24 ± 47.25	85.32 ± 9.34	200.91 ± 22.87	64.34 ± 8.88	66.27 ± 10.38	95.69%	300
BOD_5 (mg L^{-1})	601.32 ± 23.65	1235.36 ± 46.34	706.52 ± 31.05	814.55 ± 30.08	54.12 ± 9.05	93.08 ± 8.63	44.31 ± 5.62	38.25 ± 3.69	95.30%	100
TN (mg L^{-1})	106.85 ± 10.33	272.13 ± 20.12	164.32 ± 10.63	165.55 ± 15.68	27.55 ± 1.55	82.32 ± 7.22	46.12 ± 2.37	48.37 ± 13.31	70.78%	150
TP (mg L^{-1})	20.26 ± 2.68	28.65 ± 1.38	30.55 ± 5.36	21.54 ± 2.64	5.85 ± 1.59	8.10 ± 1.00	7.05 ± 0.52	5.15 ± 0.84	76.09%	—
TSS (mg L^{-1})	163.81 ± 26.97	320.11 ± 26.36	195.33 ± 24.85	198.02 ± 16.95	19.58 ± 3.12*	46.74 ± 1.08	14.65 ± 1.25	12.65 ± 1.66	93.61%	150
pH	7.25 ± 0.05	7.54 ± 0.13	7.36 ± 0.17	7.48 ± 0.10	7.12 ± 0.04	7.58 ± 0.22	7.21 ± 0.14	7.40 ± 0.12	—	5.5 – 9
Chloride	265.82 ±12.54	322.50 ±26.50	285.12 ±20.65	235.43 ±30.25	312.26 ±35.35	348.38 ±30.50	315.05 ±16.52	360.25 ±44.10	—	≤ 600
Arsenic (As) (mg L^{-1})	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	—	≤ 0.1
Cadmium (Cd) (mg L^{-1})	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	—	≤ 0.01
Total Chromium (Cr) (mg L^{-1})	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	—	≤ 0.5
Mercury (Hg) (mg L^{-1})	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	—	≤ 0.002
Lead (Pb) (mg L^{-1})	n.d	n.d	n.d	n.d	n.d	n.d	n.d	n.d	—	≤ 0.05
E. coli (CFU 100 mL^{-1})	11,500 ± 1,500	10,800 ± 2,300	9,700 ± 1,700	6,600 ± 2,500	15	17	n.d	n.d	100%	≤ 200

Remark: Values are presented as the mean ± standard deviation (SD) based on triplicate analyses (n = 3). "—" = "no regulations". "n.d" = "Not detected". "LOD"= "Limit of detection". LOD (As) = 0.0001 mg L^{-1}. LOD (Cd) = 0.5 µg L^{-1}. LOD (Cr) = 0.005 mg L^{-1}. LOD (Hg) = 0.1 µg L^{-1}. LOD (Pb)= 0.005 mg L^{-1}. LOD (E. coli) = 1 CFU 100 mL^{-1}.

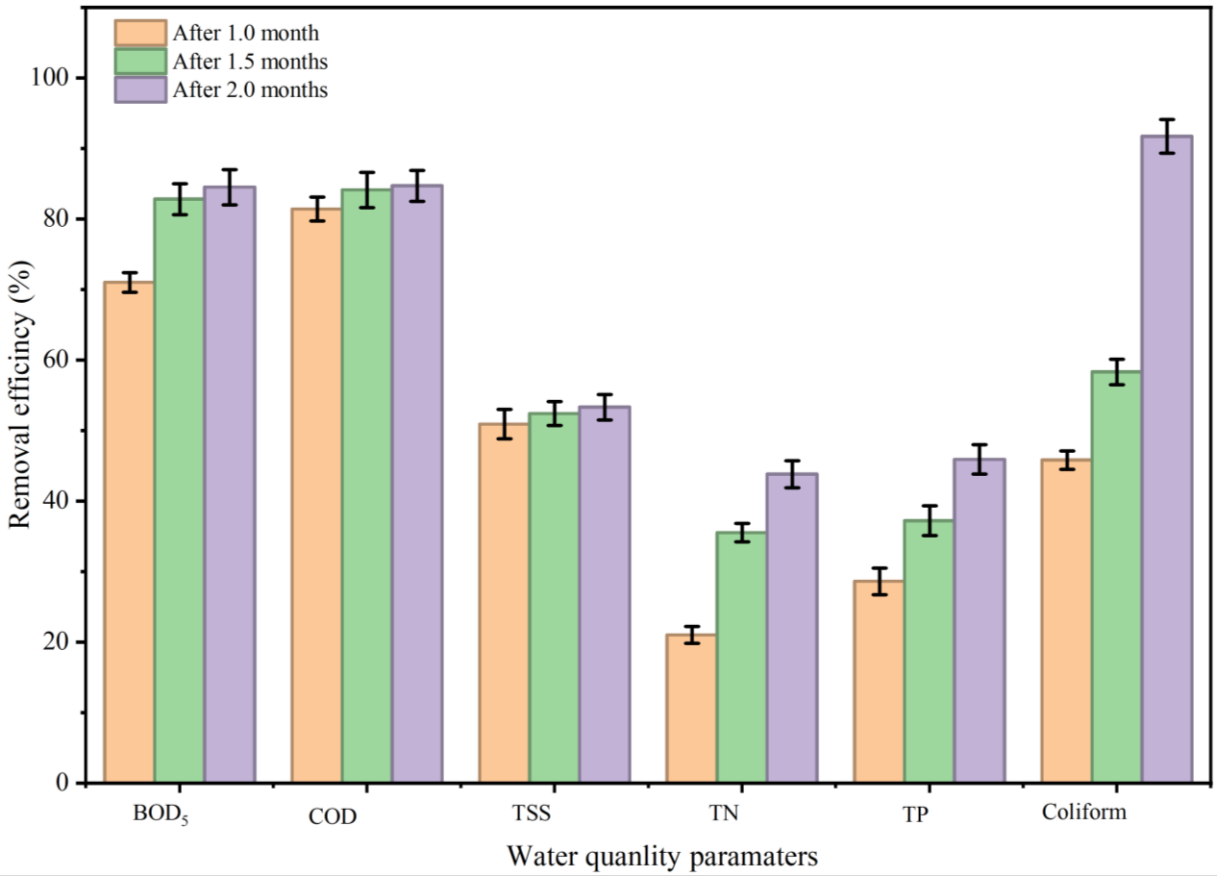


Figure 2 Pollutant removal efficiency (%) across the integrated decentralized treatment train at three operational stages: after 1 month, after 1.5 months, and after 2 months (design flow 12–15 m^3 day^{-1}).

In contrast, nutrient removal was intentionally moderate and increased gradually: total nitrogen removal increased from 21.0% after 1 month to 35.5% at 1.5 months and 43.8% at 2 months, whereas total phosphorus removal increased from 28.6% to 37.2% and then to 45.9%. This controlled retention preserved approximately 115.6±7.5 mg TN L^{-1} and 12.5±1.3 mg TP L^{-1} in the final effluent—concentrations well suited for direct agricultural reuse as liquid fertilizer without the need for additional nutrient supplementation. Pathogen removal showed the most dramatic improvement, increasing from 45.8% after the first month to 58.3% at 1.5 months and reaching 91.7% (equivalent to a 1.08 log reduction) by the second month. This strong final performance is attributed to the combined effects of filtration, predation, and antimicrobial activity in the densely rooted elephant grass wetland bed. The data in Figure 2 confirm that the system required approximately 1.5 months of maturation to achieve stable, high-level performance. Once mature, it resulted in >84% removal of organic matter, 44–46% nutrient retention for reuse, and effective pathogen reduction, all while operating at very low energy consumption (0.25 kWh m^{-3}). This progressive stabilization pattern is characteristic of nature-based hybrid systems in tropical climates, where higher temperatures accelerate microbial and plant processes, biofilm establishment, and root-zone development (Corrêa et al., 2025; Monteagudo-Hernández et al., 2024; Torrens et al., 2021).

Notably, the system was monitored under steady-state conditions for approximately three months following commissioning in October 2023, with detailed sampling at 1, 1.5, and 2 months of operation. This period captured the critical maturation phase, during which the elephant grass root system developed vigorously (>150 cm in height) and the microbial biofilms stabilized, resulting in high and consistent removal efficiency. While this timeframe demonstrates rapid stabilization typical of tropical conditions (where elevated temperatures increase microbial activity and plant growth (Corrêa et al., 2025; Monteagudo-Hernández et al., 2024; Torrens et al., 2021), we acknowledge that longer-term monitoring across multiple seasons is necessary to fully evaluate resilience to hydraulic fluctuations, monsoon variability, and long-term media clogging or plant dynamics. Future studies will extend the observation period to at least 12–24 months.

2) Feasibility of water reuse for agriculture

To assess the agronomic feasibility of using polished piggery effluent as a complete liquid fertilizer substitute, a field experiment was conducted on *Brassica juncea* (mustard greens), a fast-growing leafy vegetable widely cultivated in northern Vietnam

because of its high nutritional value and short growth cycle. The trial was structured as a randomized complete block design (RCBD) with three replicates, which helped ensure statistical reliability and accounted for inherent spatial variability across the experimental site. Each plot measured 2 m × 3 m (6 m^2) and was established at a planting density of 25 plants m^{-2}, corresponding to an approximate population of 250,000 plants per hectare, which aligns with intensive production practices commonly adopted in the region. Plant height is a key morphological parameter for evaluating vegetative growth and yield potential in leafy vegetables such as *Brassica juncea*. The increase in plant height is governed by both the cultivar's intrinsic genetic factors and extrinsic environmental and agronomic conditions. Among these factors, nutrient availability—particularly the type and rate of fertilization—exerts a strong influence. Even within the same cultivar and at the same growth stage, differences in fertilizer regimes can lead to substantial variations in plant height development. The effects of different nutrient management treatments on the temporal dynamics of plant height in *Brassica juncea* are presented in Table 4.

The plant height increased most rapidly during the 10–20 days after transplanting across all the treatments. The growth rate subsequently slowed and stabilized between 20 and 30 days after transplanting. Significant differences in plant height among the nutrient management treatments became evident from 20 days onward. At 30 and 40 days after transplanting, plants under CT4 (recycled effluent combined with high-dose compost) achieved the greatest height, which was significantly greater than that of the other treatments. In contrast, plant height in CT3 was significantly lower than that in the other treatments at the 5% probability level ($p < 0.05$). Increasing crop yield is the primary objective of agricultural production. Yield is influenced by both genetic factors inherent to the cultivar and external factors such as the growing season, cultivation practices, temperature, humidity, light, and, in particular, fertilization. The effects of different nutrient management treatments on the yield and yield components of *Brassica juncea* are presented in Table 5.

The yield performance clearly increased with increasing compost application rate: CT2 < CT1 < CT3 < CT4. Among all the treatments, CT2 (recycled effluent + 5 t ha^{-1} compost) resulted in the lowest growth and yield. The total fresh weight per plant was only 69.23 g, and the actual marketable yield reached just 21.46 t ha^{-1}, which was significantly lower than that of the conventional chemical fertilizer control (CT1; 36.85 t ha^{-1}). These results indicate that the combination of recycled effluent with a low compost rate (5 t·ha^{-1}) did not supply sufficient nutrients to meet the high nutrient demand of *Brassica juncea*, resulting in poor growth and substantial yield reduction. When the compost rate was increased to 10 t ha^{-1} (CT3), the recycled nutrient system began to outperform conventional chemical fertilization. In CT3, the total fresh weight per plant reached 100.62 g, and the actual marketable yield was 38.38 t ha^{-1}, which was significantly greater than that in CT1. Compared with synthetic NPK fertilizer alone, the balanced nutrient supply from the combination of treated effluent and moderate compost application supported better plant growth. Treatment CT4 (recycled effluent + 15 t ha^{-1} compost) resulted in the highest yield parameters, which were significantly greater than those of all the other treatments. The marketable fresh weight per plant reached 100.93 g, resulting in the highest actual marketable yield of 45.05 t ha^{-1}. The high organic matter input not only fully replaced the reduced chemical fertilizer but also likely improved soil physical properties and nutrient availability for root uptake. These findings demonstrate that treated piggery wastewater combined with compost can completely replace chemical fertilizers and increase *Brassica juncea* yield, provided that an adequate compost rate is applied. A low compost dose (as in CT2) led to severe yield penalties, whereas moderate-to-high rates (10–15 t ha^{-1} in CT3 and CT4) resulted in superior agronomic performance compared with conventional practices.

Table 4 Plant height (cm) of *Brassica juncea* on different days after sowing (DAS) under various nutrient management treatments

Treatment	Days			
	10	20	30	40
CT1 – Conventional chemical fertilizer (Control)	5.09^{b}	13.74^{d}	17.04^{e}	20.07^{e}
CT2 – Recycled effluent + low-dose compost (5 t ha^{-1})	5.27^{b}	16.04^{c}	18.05^{d}	21.01^{d}
CT3 – Recycled effluent + medium-dose compost (10 t ha^{-1})	5.26^{b}	15.82^{c}	19.75^{c}	22.54^{c}
CT4 – Recycled effluent + high-dose compost (15 t ha^{-1})	6.26^{a}	18.65^{b}	21.31^{b}	24.52^{b}

Remark: Values represent treatment means (n = 3). Means followed by different letters within the same column are significantly different at $p < 0.05$ according to Tukey's HSD test.

Leafy vegetables such as *Brassica juncea* are subject to strict food safety regulations in many countries, including Vietnam, particularly regarding nitrate (NO_3^-), heavy metal, and *E. coli* contamination. The accumulation of these contaminants in vegetables is influenced by multiple factors, including soil properties, irrigation water quality, fertilizer type and rate, and other cultivation practices. Among these factors, nitrogen fertilization has the strongest effect on nitrate accumulation in leafy vegetables. The concentrations of nitrate, heavy metals, and *E. coli* in *Brassica juncea* under different nutrient management treatments are presented in Table 6.

While the agronomic benefits are clear, food safety is paramount when treated livestock wastewater is reused for edible crops such as *Brassica juncea*. The polished effluent achieved a 91.7% reduction in coliforms (to 1,000 MPN 100 mL^{-1}), meeting Vietnamese discharge standards (QCVN 62-MT:2016/BTNMT Column B). It is acknowledged, however, that total coliforms serve solely as indicator parameters. Comprehensive pathogen monitoring (e.g., *E. coli*, *Salmonella* spp., *helminth* eggs) and crop tissue analysis were not performed within the scope of this pilot study. The hybrid system design incorporates multiple barriers—mechanical separation, biological degradation, and subsurface filtration/root-zone predation—that are known to effectively reduce bacterial and parasitic pathogens in elephant grass wetlands, as shown by studies on CW pathogen removal in tropical livestock wastewater. Nevertheless, the potential risks of heavy metal accumulation (from pig feed) in soil and crops, as well as viral or antibiotic-resistant bacteria, warrant further investigation. No visible crop contamination or quality issues were observed, but this remains a limitation.

The actual marketable yield under the recycled nutrient system (T2) reached 45.05±2.8 t ha^{-1}, a 23.6% increase over that of the conventional control (T1, 36.46±2.3 t ha^{-1}) (Table 7). These results demonstrate that when combined with onsite compost, the polished effluent not only fully replaced synthetic NPK fertilizers but also conferred a clear agronomic advantage, enhancing overall crop productivity within a circular nutrient management framework. A deeper mechanistic analysis revealed that the enhanced performance in T2 stems from multiple synergistic effects that are not achievable with chemical fertilizers alone. First, the polished effluent provides a continuous supply of readily available nutrients, particularly nitrogen as ammonium (NH_4^+-N) and phosphorus as orthophosphate (PO_4^{3-}-P), delivered incrementally throughout the day via drip or furrow irrigation. This avoids the episodic "feast-or-famine" dynamics associated with single basal applications of synthetic fertilizers, ensuring more stable nutrient uptake during critical growth phases. Second, the incorporation of compost at 15 t ha^{-1} stimulated soil microbial activity, promoted enhanced nutrient mineralization, improved root-zone aeration, and increased organic matter turnover. Third, the elevated organic matter content in the T2 plots improved the soil structure and water-holding capacity, thereby reducing nutrient leaching losses, which is particularly relevant under tropical rainfall regimes characterized by intense, episodic precipitation. Fourth, both the effluent and the compost contributed essential micronutrients (e.g., Fe, Zn, and Mn) that are absent or limited in standard NPK formulations, thereby supporting key physiological processes such as chlorophyll synthesis, enzyme activation, and overall metabolic efficiency.

Table 5 Effect of nutrient management treatments on the yield and yield components of *Brassica juncea*

Treatment	Total fresh weight per plant (g)	Marketable fresh weight per plant (g)	Theoretical yield (t ha^{-1})	Actual marketable yield (t ha^{-1})
CT1 – Conventional chemical fertilizer (Control)	94.33^{b}	83.51^{d}	42.35^{e}	36.85^{d}
CT2 – Recycled effluent + low-dose compost (5 t ha^{-1})	69.23^{d}	59.40^{b}	31.64^{d}	21.46^{c}
CT3 – Recycled effluent + medium-dose compost (10 t ha^{-1})	100.62^{c}	92.25^{c}	46.38^{c}	38.38^{b}
CT4 – Recycled effluent + high-dose compost (15 t ha^{-1})	116.40^{a}	100.93^{a}	51.22^{b}	45.05^{a}
$LSD_{0.05}$	0.51	0.54	0.75	1.28
CV (%)	0.17	0.34	0.87	1.85

Remark: Values represent treatment means (n = 3). Means followed by different letters within the same column are significantly different at $p < 0.05$ according to Tukey's HSD test.

Table 6 Nitrate and heavy metal concentrations in *Brassica juncea* under different nutrient management treatments

Treatment	NO_3^- (mg kg^{-1})	Pb (mg kg^{-1})	Hg (mg kg^{-1})	Cd (mg kg^{-1})	As (mg kg^{-1})	*E. coli* (MPN g^{-1})
CT1	235.56 ± 14.63	n.d.	n.d.	n.d.	n.d.	n.d.
CT2	251.17 ± 22.16	n.d.	n.d.	n.d.	n.d.	n.d.
CT3	250.70 ± 12.48	n.d.	n.d.	n.d.	n.d.	n.d.
CT4	202.42 ± 14.08	n.d (LOD=0.005)	n.d.	n.d.	n.d.	n.d.
QCVN 8-2:2011/BYT & QCVN 8-3:2012/BYT	500	0.3	0.05	0.1	0.2	-

Remark: Values are presented as the mean ± standard deviation (SD) on a fresh weight basis (n = 3). "—" = "no regulations". "n.d" = "Not detected". "LOD"= "Limit of detection".

LOD (Pb)= 0.05 mg/kg. LOD (Hg) = 0.005 mg/kg. LOD (Cd) = 0.002 mg/kg. LOD (As) = 0.002 mg/L. LOD (E. coli) = 1 CFU/g.

QCVN 8-2:2011/BYT: National Technical Regulation on Heavy Metal Limits in Food. QCVN 8-3:2012/BYT: National Technical Regulation on Microbiological Contamination in Food.

Table 7 Yield and yield components of *Brassica juncea* under the two nutrient regimes

Treatment	Fresh weight (g $plant^{-1}$)	Theoretical yield (t ha^{-1})	Actual marketable yield (t ha^{-1})
T1 – Conventional chemical fertilizer	96.23±4.2	42.34±2.1	36.46±2.3
T2 – Recycled effluent + optimal compost	116.40±5.6	51.22±3.4	45.05±2.8

Remark: Values are presented as the mean ± standard deviation (SD) of three replicates (n = 3).

These integrated mechanisms account for the observed divergence in growth trajectories, with advantages becoming more pronounced approximately 20 days after sowing (DAS), which coincides with the peak nutrient-demand period in leafy vegetables such as *Brassica juncea*. These results align with and exceed comparable findings in recent literature on the reuse of treated livestock wastewater combined with organic amendments. For instance, studies on leafy vegetables such as lettuce and Chinese cabbage have shown yield enhancements of 10–35% when organic fertilizers or treated effluents replace or supplement chemical inputs, driven by improved soil fertility, sustained nutrient release, and enhanced microbial activity (Liu et al., 2025; Zhang et al., 2024). Similarly, field trials and meta-analyses have confirmed that compared with conventional fertilization, integrating treated swine wastewater or biogas slurry with compost or other organic amendments can increase the marketable biomass of leafy crops by 8–30%, which is attributed to improved nutrient bioavailability, reduced environmental losses, and synergistic improvements in soil health (Libutti et al., 2023; Wang et al., 2023; Xiang et al., 2022). These synergies underscore the potential of resource-oriented sanitation systems to increase agronomic outcomes while advancing circular economy principles in tropical smallholder and decentralized settings.

3) Economic and environmental benefits

The integrated wastewater treatment and resource recovery system implemented at Battalion 3 exemplifies a circular-economy-oriented approach by concurrently mitigating environmental pollution and delivering quantifiable economic returns in a decentralized, resource-constrained military setting. By mechanically separating high-strength piggery wastewater into liquid and solid fractions, the system converts the liquid stream into nutrient-enriched polished effluent suitable for fertigation. It transforms separated solids into high-quality compost. This approach effectively closes the nutrient loop, eliminates reliance on external synthetic chemical fertilizers, and prevents the discharge of organic pollutants and excess nutrients into the environment, thereby addressing key challenges such as localized eutrophication, oxygen depletion, and soil/water contamination, which are prevalent in tropical livestock operations (Chen et al., 2024).

A comprehensive cost–benefit analysis, which was based on the field trial results with *Brassica juncea* (Table 4), highlights substantial advantages across both economic and environmental dimensions (Table 8). In the conventional system (T1), the chemical fertilizer costs totaled 5,200,000 VND per hectare per crop cycle, whereas the irrigation water costs amounted to 700,000 VND (based on 350 m^3 of freshwater). The recycled system (T2) achieved the complete elimination of these expenditures by fully substituting polished effluent and onsite compost, resulting in 100% savings in fertilizers and irrigation water. Coupled with a 23.6% increase in marketable yield (from 36.46±2.3 t ha^{-1} to 45.05±2.8 t ha^{-1}), this translated to additional revenue of approximately 25,770,000 VND ha^{-1} $cycle^{-1}$ (assuming a conservative farm-gate price of 3,000 VND kg^{-1} for fresh mustard greens, reflective of 2023–2024 northern Vietnam averages). The resulting net economic benefit was estimated at ≈31.67 million VND ha^{-1} $cycle^{-1}$, demonstrating operational economic advantages even under modest yield assumptions and without accounting for long-term soil health improvements or avoided environmental remediation costs.

Table 8 Comparison of the partial economic benefits of the circular nutrient recovery system with those of conventional practices

Item	Conventional (T1)	Recycled System (T2)	Benefit/saving
Chemical fertilizer cost	5,200,000 VND	0 VND	5,200,000 VND (100% saving)
Irrigation water cost	700,000 VND (350 m^3)	0 VND (reused effluent)	700,000 VND
Yield (marketable)	36.46±2.3 t ha^{-1}	45.05±2.8 t ha^{-1}	+8.59 t ha^{-1} (+23.6%)
Additional revenue from yield	–	–	+25,770,000 VND
Net economic benefit	–	–	≈ 31.67 million VND·ha^{-1} $cycle^{-1}$

Remark: Economic indicators were calculated on a hectare-per-crop-cycle basis under pilot-scale conditions. Additional revenue was estimated using a farm-gate price of 3,000 VND kg^{-1} for fresh mustard greens.

The figures presented in Table 8 reflect direct operational and agronomic benefits (savings on chemical fertilizers and freshwater, together with additional crop revenue) realized during the pilot trial. It is important to note that this assessment does not constitute a complete lifecycle technoeconomic analysis. Important cost components, such as capital investment for construction of the equalization tank, biological reactor, wetland bed and liner, procurement of the screw-press separator, ongoing maintenance and media replacement, labor inputs, electricity for minimal pumping, and any costs related to compost maturation and handling, were not fully quantified in the present study.

In the specific context of a military battalion, many of these costs were mitigated by using locally sourced materials, onsite labor by soldiers, and a predominantly gravity-flow design. For example, electricity consumption remained low at 0.25 kWh m^{-3}. Nevertheless, we acknowledge that in other settings, these elements could vary considerably. Preliminary considerations and a simple sensitivity discussion are provided in the Supplementary Information. Future research could develop a more detailed cost–benefit analysis, including amortized capital costs over the expected 15–20-year service life of constructed wetland systems, to support broader implementation. These economic gains align with broader evidence from international studies on nutrient recovery and wastewater reuse in agriculture. For instance, meta-analyses and field evaluations of treated livestock effluents combined with organic amendments have shown fertilizer cost reductions of 50–100% alongside yield increases of 10–35% in leafy vegetables, driven by sustained nutrient bioavailability and reduced input dependence (Orner et al., 2021; Pausta et al., 2024). Similarly, circular nutrient recovery from manure and wastewater in livestock-dense regions has been associated with net present values exceeding initial investments and benefit–cost ratios of 3–4 or higher, particularly when freshwater extraction is avoided, reduced chemical fertilizer production emissions, and increased crop revenue (Linh et al., 2026; Pausta et al., 2024). In tropical Asian contexts, such as Vietnam, integrated piggery wastewater recycling has demonstrated potential for substantial economic resilience through resource valorization, with savings on water and fertilizers offsetting treatment costs while promoting closed-loop systems that minimize external resource imports (Chen et al., 2024).

Environmentally, the system prevents the annual discharge of several tons of COD, BOD_5, and nutrients (based on a processing capacity of 12–15 m^3 day^{-1}), thereby averting eutrophication risks and conserving freshwater resources in a region prone to seasonal shortages. Recycling organic matter via compost and effluent enhances soil structure, microbial diversity, and long-term fertility, which benefits unattainable with synthetic fertilizers alone. These outcomes support global sustainability frameworks, including reduced greenhouse gas emissions from fertilizer manufacturing and the mitigation of nutrient loss, which are consistent with circular economy principles in decentralized livestock systems across developing tropical regions (Orner et al., 2021; Soo et al., 2024).

The promising operational performance observed over the three-month monitoring period supports the stability and effectiveness of the hybrid system in a tropical military setting. However, as with many pilot studies, conclusions regarding long-term scalability and sustainability should be tempered by the relatively short duration. Seasonal influences (e.g., heavy rainfall in northern Vietnam) and cumulative effects on wetland media and vegetation warrant extended evaluation. Taken together, these operational benefits highlight the potential economic attractiveness of the proposed circular model in resource-limited decentralized settings. Moreover, the authors recognize that a more complete evaluation incorporating all capital and recurring costs would provide additional clarity for decision-making.

Overall, this hybrid, low-energy system (0.25 kWh m^{-3}) offers a replicable blueprint for military battalions, rural communities, and smallholder pig farms in tropical developing countries, balancing technical performance, economic attractiveness, and environmental stewardship within a circular-economy framework. Wider adoption could significantly contribute to national goals in terms of water security, nutrient management, and sustainable agriculture. The public health implications of wastewater reuse in food production are a global concern. In this military context, onsite production and consumption reduce transport risks, but adherence to WHO guidelines (e.g., <1,000 *E. coli MPN*·100 mL^{-1} for restricted irrigation, with more stringent requirements for leafy vegetables) and Vietnamese reuse standards

(QCVN 01-195:2022/BNNPTNT) is essential. Future work should include microbial and heavy-metal testing of crops, as well as risk assessment.

Conclusions

In this study, a decentralized, integrated wastewater treatment and resource recovery system for military battalion in northern Vietnam was developed and evaluated. The hybrid configuration, comprising mechanical solid–liquid separation, a combined anaerobic–aerobic biological reactor, and a subsurface-flow constructed wetland planted with elephant grass, effectively treated high-strength piggery wastewater while recovering nutrients and organic matter for agricultural reuse. Over a 10-month monitoring period, the system achieved stable removal efficiencies of 84.5% for BOD_5, 84.7% for COD, 53.3% for TSS, and 91.7% for coliform after the initial maturation phase, consistently meeting Vietnamese discharge standards. The polished effluent, when combined with onsite compost, supported *Brassica juncea* production under different nutrient management regimes. Compared with conventional chemical fertilization, treatment involving recycled effluent plus high-dose compost achieved significantly higher marketable yields. Nitrate and heavy metal concentrations in harvested vegetables remained within Vietnamese food safety limits, and *E. coli* levels were low or undetectable.

The system demonstrated clear circular economy advantages through the substitution of synthetic fertilizers and the generation of net economic benefits. However, this study was limited to a single-cropping season and a 10-month monitoring period. A full nutrient mass balance, long-term system performance under varying climatic conditions, and comprehensive pathogen risk assessment in crops were not conducted. Future research should address these aspects to strengthen the evidence base for wider adoption.

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Data availability statement

Information and data used in the study will be disclosed upon request.

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Conflicts of interest

The authors declare that there are no conflicts of interest in competing financial or personal relationships that could have appeared to influence the work reported in this work.

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